

Optimization models of stand structure and selective cutting cycle for large diameter trees of broadleaved forest in Changbai Mountain

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Abstract: The optimum models of harvesting yield and net profits of large diameter trees for broadleaved forest were developed, of which include matrix growth sub-model, harvesting cost and wood price sub-models, based on the data from Hongshi Forestry Bureau, in Changbai Mountain region, Jilin Province, China. The data were measured in 232 permanent sample plots. With the data of permanent sample plots, the parameters of transition probability and ingrowth models were estimated, and some models were compared and partly modified. During the simulation of stand structure, four factors such as largest diameter residual tree (L_{DT}), the ratio of the number of trees in a given diameter class to those in the next larger diameter class (q), residual basal area (R_{BA}) and selective cutting cycle (C) were considered. The simulation results showed that the optimum stand structure parameters for large diameter trees are as follows: q is 1.2, L_{DT} is 46cm, R_{BA} is larger than 26 m² and selective cutting cycle time (C) is between 10 and 20 years.

Keywords: Large diameter tree; Stand structure; Optimization; Broad-leaved forest; Model

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Introduction

The volume of broadleaved Korean pine (*Pinus koraiensis*) forests and coniferous-broadleaved mixed forests in Changbai Mountain region is decreasing, while the volume of broadleaved forests is increasing as a result of human disturbance for a long time. In Forestry Administration Bureau of Yanbian Korean Nationality Autonomous Prefecture, during the period of 1985–2000, the volume of Korean pine reduced by 3343 000 m³, while the total volume of *Manchurian ash*, *Juglans mandshurica*, *Quercus mongolica* and *B. castata* in broadleaved forests increased by 14 443 000 m³. In addition, the volume of mature and over mature forest decreased by 36 353 000 m³ and that of near mature forest increased by 41 351 000 m³ for repetitive harvesting operation. The volume decrease of mature and over mature forests and repetitive harvesting operation have resulted in the serious shortage of precious broadleaved large diameter trees in Changbai Mountain region, which is in contradiction with the increasing demand for large diameter trees.

The cultivation for large diameter trees in broadleaved forest can not only satisfy with the demand of consumers, but also improve the productive force, economic benefits and ecological benefits of stands. Forest selective cutting and intermediate cutting are regarded as optimum management approaches in sustainable forest utilization. However, the efficiency of those cutting methods in practice depends on determination of reasonable parameters of stand structure and selective cutting cycle, which is a rather complicated process, so the optimum method is often used.

The optimum method was first applied to uneven-aged forest

by Adams and Ek (1974). After then, many researches have been conducted on harvesting optimization from different aspects (Hann *et al.* 1979; Gove *et al.* 1992; Volin *et al.* 1996; G.A.Mendoza *et al.* 1986). The growth model is the basis of the optimization method for uneven-aged forest because predicting growth status of stands in the future under different harvesting plans is the key factor of sustainable forest utilization (Kimmins 1990).

In this paper, we mainly focused on: (1) determining optimal factors and optimal selective cutting cycle of stand structures in broadleaved forest with large diameter trees by harvesting optimization models based on matrix growth model, harvesting cost and wood price models; (2) developing and testing both dynamic transition probability and ingrowth models with data obtained from Hongshi Forestry Bureau, Changbai Mountain area, which are used in the matrix growth model to simulate forest growth; (3) constructing a dynamic variable harvesting cost model used in the optimization model to simulate variable harvesting cost in each harvesting operation.

Optimal models of stand structure and selective cutting cycle for large diameter trees

Optimal model contains objective functions, which is to seek maximum harvesting yield of large diameter tree and net profits of cutting trees in certain time, and constraints such as stand growth, harvesting cost and wood price. It is used to simulate the effect of different stand structures and selective cutting cycle on objective function for gaining optimal stand structure and optimal selective cutting cycle of broadleaved forest. In the simulations of optimal stand structure, selective management mode is adopted during planning period, but clear cutting is used for the last cutting in planning period. The optimal models are:

$$\begin{aligned} \text{Max } Z_1 = & \sum_{k=1}^{m-1} \left(\sum_{i=1}^n (h_{ki} V_i L_{ji}) - C_k \right) (1+p)^{-c(k-1)} + \\ & \left(\sum_{i=1}^n (N_i V_i L_{ji}) - C_m \right) (1+p)^{-T} \end{aligned} \quad (1)$$

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$$\text{Max } Z_2 = \sum_{k=1}^{m-1} \sum_{i \geq 7}^n (h_{ki} V_i) + \sum_{i \geq 7}^n (N_i V_i) \quad (2)$$

where, Z_1 is the net profits of harvesting trees (Yuan), Z_2 the sum of harvesting yield of largest diameter trees (D.B.H ≥ 30 cm) during planning period (m^3), h_{ki} the number of trees cut in diameter class i in k^{th} cutting, V_i the average volume of one single tree (m^3), L_{ji} the average price of trees in diameter class i (Yuan), C_k the sum of wood productive cost in cutting area in k^{th} cutting (Yuan), p the interest rate, C the selective cutting cycle (a), N_i the number of trees in diameter class i at the end of planning period (trees/ hm^2), C_m the wood productive cost in cutting area at the end of planning period, that is, productive cost of clear cutting (Yuan), T the planning period (year), m the cutting times during planning period (if the remainder of t/c is 0, then: $m = 1 + \text{INT}(T/C)$, or $m = 2 + \text{INT}(T/C)$), and n the diameter class.

Constraints of stand growth for optimal models

The models that describe the growth of trees are called tree growth model. There are many such models, in which matrix growth model proposed by Buongiorno and Michie (1980) is applied in the paper. In the model, the stand transition from one status to other status is expressed by transition matrix. The precision of matrix model is up to transition probabilities such as a_{ii} , b_{ii} and the number of ingrowth trees (I_i). According to the difference of stand structures, these parameters are allowed to adopt static constants and dynamic variables. In uneven-aged broadleaved forest, the analysis results for dynamic transition probability model and ingrowth model are closely in accordance with the regulation of stand growth variation. Dynamic transition probability model is based on the hypothesis that growth variation of stand diameters is affected by stand density, especially residual basal area of stands. According to the principle, Lin and Buongiorno (1997) proposed two-parameter model:

$$\begin{aligned} a_{ii} &= \beta_{10} + \beta_{11} R_{BA} \\ b_{ii} &= \beta_{12} + \beta_{13} R_{BA} \\ m_{ii} &= \beta_{14} + \beta_{15} R_{BA} \\ a_{ii} + b_{ii} + m_{ii} &= 1 \end{aligned} \quad (3)$$

where, a_{ii} , b_{ii} and m_{ii} respectively represents the transition probabilities of trees staying in the same diameter class, advancing to the next diameter class and the mortality for diameter class i over time t to time $t+\theta$. θ is the period interval between inventory (5a). R_{BA} is the residual basal area after harvesting in time t (m^2/hm^2). β_{10-15} is the estimated parameters of the model and i is diameter class (1, 2, 3, ..., n).

In addition, the ingrowth of stands is relevant to stand density, which increases as the increment of residual trees and decreases as the increment of residual basal area. The ingrowth model built by Ek (1974) is:

$$I_t = \beta_0 + \beta_1 \sum_{i=1}^n B_i (y_{it} - h_{it}) + \beta_2 \sum_{i=1}^n (y_{it} - h_{it}) \quad (4)$$

where, B_i is the single basal area in diameter class i , y_{it} the

number of stands in diameter class i in time t , h_{it} the number of trees cut in diameter class i in time t , and $\beta_0, \beta_1, \beta_2$ are estimated parameters.

Constraints of harvesting operation for optimal models

The productive cost of harvesting operation means direct productive cost in cutting area, which includes the cost of logging, delimbing, skidding, loading, clearing cutting area and so on. The calculation of cost is rather complicated because it is affected by many factors of cutting area, but when the operation condition is determined, the relation model of productive cost in cutting area can be simple as follows:

$$C_m = f(\omega_1, \omega_2) = A + B\omega_1 / \omega_2 \quad (5)$$

where, C_m is the productive cost in cutting area (Yuan/ hm^2), ω_1 the volume of cutting trees per hectare (m^3/hm^2), ω_2 the volume of single cutting tree, and A, B are constants.

Estimation of parameters in the models

Conditions of plots

The data used in transition probability model and ingrowth model are from 232 permanent sample plots (including re-measured sample plots) of Hongshi Forestry Bureau in Changbai Mountain area. The permanent sample plots were established and data were measured in 1975 and 1980. The data of sample plot established in 1975 were re-measured 6 times, separately in 1980, 1986, 1990, 1994, 1999 and 2003. And data of sample plots established in 1980 were re-measured 5 times, separately in 1986, 1990, 1994, 1999 and 2003. The area of permanent sample plot is 0.06 hm^2 . In sample plots, management pattern is the same with that in cutting area. Therefore, different cutting methods were practiced in sample plots, including selective cutting with different cutting intensity, intermediate cutting, clear cutting and unlawful cutting, and cutting time and cutting cycle are different. As some sample plots have different re-measured periods, linear processing method is applied to ensure that all the sample plots have the same re-measured periods of 5 years. In the sample plots, broadleaved forest account for 90%, of which *Manchurian ash*, *Q. Mongolica*, *Juglans Mandshurica*, *Elm* and *Tilia* take up more than 66.6%.

Statistics method for plots

Transition probability model and ingrowth model are relevant to residual basal areas of stands, so permanent sample plots need to be grouped by residual basal areas of stands. First, 232 sample plot data are analyzed in statistical method and the residual basal area of every plot is calculated. Then, the sample plots are ordered by the size of residual basal area, from small to large. Then, the sample plots are grouped according to residual basal areas. Each group has the same basal area after integer to residual basal area. If the number of the plots in a group is less than 3, the neighboring groups will be amalgamated. In this way, all the plots are divided into 26 groups. For every group, residual basal area per hectare, number of trees per hectare, transition probability of every diameter class and number of ingrowth trees per hectare are separately calculated in statistical method. The software SPSS is used to estimate the parameters in the models.

Parameter estimation for transition probability model

Besides two parameters in model (3), the parameters in the following models are also estimated. The statistical results indicate that the Eqs. (3), (6) and (10) have better correlation. The results are shown in Table 1 ($[a] = a_{it}$).

$$[a] = a + b \cdot R_{BA} + c/n \quad (6)$$

$$[a] = a + b \cdot R_{BA} + c \cdot n \quad (7)$$

$$[a] = a + b \cdot R_{BA} + c \cdot R_{BA}/n \quad (8)$$

$$[a] = a + b \cdot R_{BA} + c + R_{BA} \cdot n \quad (9)$$

$$[a] = a + b \cdot R_{BA}^{1/2} \quad (10)$$

where, a , b , c are the estimated parameters of the models, and n represents the total number of trees in t time.

The coefficients of determination of the three models in Table 1 show that the correlation is ranked from the best to the worst as follows: model (6), model (10) and model (3). From Table 2 and Table 3, the correlation of transition probability model becomes weak as the increment of diameter class. This indicates that the effect of residual basal area and number of stands on the growth of trees decreases as the increment of diameter class. When diameter class is bigger than 22 cm, the correlation between transition probability and residual basal area & the number of stands is weaker. This indicates that the effect of residual basal area and the number of stands on transition probability is smaller. Therefore, transition probability can adopt constant, static transition probability in Table 4.

Table 1. Coefficients of determination for a_{it} and b_{it} in each transition probability model

Diameter class (cm)	Coefficients of determination (R^2)					
	Model (3)		Model (10)		Model (6)	
	a_{it}	b_{it}	a_{it}	b_{it}	a_{it}	b_{it}
6	0.42416	0.43921	0.51200	0.54875	0.61893	0.77099
10	0.40459	0.48397	0.47688	0.55003	0.50546	0.60381
14	0.45308	0.45855	0.53337	0.52327	0.59801	0.55237
18	0.26091	0.27287	0.30186	0.30592	0.45879	0.40891
22	0.27623	0.34292	0.32675	0.39194	0.38240	0.44656

Note: a_{it} is the transition probability of trees staying in the same diameter class for diameter class i over time t to time $t+\theta$; b_{it} is transition probability of trees advancing to the next diameter class for diameter class i over time t to time $t+\theta$; m_{it} is the mortality for diameter class i over time t to time $t+\theta$.

Table 2. Parameter estimation for transition probability model a_{it} ($a_{it} = a + b \cdot R_{BA} + c/n$)

Diameter class (cm)	Coefficient(a)	SE	Coefficient(b)	SE	Coefficient(c)	SE	R^2	DF-RES
6	0.7462	0.0555	0.0032	0.0012	-91.8990	26.8025	0.6189	23
10	0.7188	0.0678	0.0039	0.0014	-69.0739	32.71184	0.5055	23
14	0.7201	0.0979	0.0062	0.0020	-136.0123	47.23383	0.5980	23
18	0.8231	0.1200	0.0043	0.0022	-191.0281	67.3543	0.4588	22
22	0.6387	0.0841	0.0034	0.0018	-80.0456	41.15834	0.3824	22

Notes: DF-RES---- freedom degree of the residuals; SE---- standard error.

Table 3. Parameter estimation for transition probability model b_{it} ($b_{it} = a_1 + b_1 \cdot R_{BA} + c_1/n$)

Diameter class (cm)	Coefficient (a_1)	SE	Coefficient (b_1)	SE	Coefficient (c_1)	SE	R^2	DF-RES
6	0.0949	0.0474	-0.0030	0.0010	123.0879	22.88261	0.7710	23
10	0.2126	0.0772	-0.0054	0.0016	98.3251	37.2782	0.6038	23
14	0.2760	0.1076	-0.0071	0.0022	113.9922	51.91716	0.5524	23
18	0.1877	0.1310	-0.0051	0.0024	165.3878	73.4995	0.4089	22
22	0.3163	0.9255	-0.0046	0.0019	91.8947	45.2728	0.4466	22

Notes: DF-RES---- freedom degree of the residuals; SE---- standard error.

Table 4. Constant transition probability

Transition probability	Diameter class (cm)									
	26	30	34	38	42	46	50	54–58	62–70	>74
a	0.6091	0.6257	0.5909	0.5929	0.6105	0.7027	0.6379	0.6061	0.6000	0.5714
b	0.3395	0.3240	0.3719	0.3786	0.3684	0.2973	0.3103	0.3333	0.3556	0.3214
m	0.0514	0.0503	0.0372	0.0286	0.0211	0.0000	0.0517	0.0606	0.0444	0.1071

Notes: when the diameter class is bigger than 50 cm, the number of stands decreases, therefore sub-group calculation is adopted; a ----transition probability of trees staying in the same diameter class for diameter class i ; b ----transition probability of trees advancing to the next diameter class for diameter class i ; m ---- mortality for diameter class i .

It is clear in Table 4 that the transition probability (a) in diameter class of 46 cm is 0.7027 which is the largest in all diameter classes. And above 74 cm, transition probability decreases to 0.57143. The variations of transition probability (a) in other diameter classes are rather small, and the average value of

a is 0.60913. The transition probability (b) in diameter classes of 34–42 cm is larger, of which transition probability in diameter class of 38 cm reaches the peak point, 0.37857. And transition probability (b) in diameter class of 46 cm falls to the lowest point, 0.2973. Mortality probability (m) decreases at first then increases

with the increment of diameters. Mortality (m) in diameter class of 46 cm falls to the lowest point, 0.0000 and in diameter class of 74 cm or higher, it reaches the peak point, 0.10714.

Estimation of parameters for ingrowth model

The parameters of ingrowth models for model (4) and model (11) to model (16) are estimated. The statistical analytical results are as follows: the correlation of model (13) with two-parameters is the best, and the coefficient of determination (R^2) is 0.72549. The correlations of Model (11), (14), (15) and (16) are better and their coefficients of determination (R^2) are 0.676 55, 0.676 41, 0.676 43 and 0.523 07, respectively. The correlation of model (4) is worse and its coefficient of determination (R^2) is 0.447 34.

Estimation parameters of model (13) are shown in Table 5.

$$I_t = a_2 + b_2/R_{BA} + c_2/n \quad (11)$$

$$I_t = a_2 + b_2 \cdot n/R_{BA} \quad (12)$$

$$I_t = a_2 + b_2 \cdot n/R_{BA}^2 \quad (13)$$

$$I_t = a_2 + b_2/R_{BA} \quad (14)$$

$$I_t = a_2 + b_2/R_{BA} + c_2 \cdot n \quad (15)$$

$$I_t = a_2 + a_2 \cdot R_{BA} + c_2/n \quad (16)$$

where, a_2 , b_2 , c_2 are parameters estimated, and n is the total number of trees in t time.

Table 5. Estimation of coefficients for ingrowth model 13 ($I_t = a_2 + b_2 \cdot n/R_{BA}^2$)

DF-RES	Sum of squares	Mean square	Sum of squares of residuals	Mean square of residuals	R^2
24	521085.437	260542.718	34245.204	1426.883	0.72549
Coefficient	Estimate	SE	CI-L	CI-U	
a_2	65.98843	10.810	43.677	88.299	
b_2	22.40485	2.813	16.599	28.211	

Notes: CI-L---- lower confidence limit; CI-U----upper confidence limit.

Simulation analysis on the optimization stand structure and selective cutting cycle

Resource conditions of compartment

The initiative conditions of the stands are as follows: the volume per hectare is 135.84 m³ before cutting, the number of trees is 381 and the residual basal area is 15.73 m². In the compartment, broadleaved trees take up 90% (volume), of which *Elms* for 17%, *Maple* for 11%, *Manchurian ash* for 15%, *Juglans mandshurica* for 8%, *Tilia* for 11%, *Acer mono* for 13%, *Q. mongolica* for 8% and other species for 7%.

Simulation analysis

In order to simulate and analyze optimum stand structures and selective cutting cycle for harvesting large diameter trees, the optimal model (1) and model (2), best correction model (6) and model (13), productive cost model (5) and stumpage price were applied. When diameter class is over 22 cm, constant transition probability in Table 4 was used for simulation. According to the research of reference (Hao *et al.* 2006), the parameters of stand structure of large diameter trees should be controlled as follows: $L_{DT} < 54$ cm, $q = 1.2-1.6$, $R_{BA} < 30$ m². In order to reveal the effect of stand structure parameters on objective function, some parameters increase as follows: L_{DT} from 30 cm to 54 cm with interval 4 cm, q from 1 to 1.6 with interval 0.1, and R_{BA} from 15 m² to 40 m² with 1-m² interval. In addition, selective cutting cycle (C) is an indispensable factor in the simulation, and increases from 5 to 30 years with five years interval.

Visual FoxPro 6.0 is used to program the optimal model. During the simulation, data tables, such as pre-harvesting stand status, stand growth simulation, stand cutting simulation, productive cost simulation and simulation results were created and set relation. Optimum stand structures and selective cutting cycles were simulated by using models (1), (2), (6), (13), (5) and those data tables. The simulating time of stand growth is 5 years. The planning period is 100 years. The operation mode of logging is as follows: skidding with J-50 skidder, cutting with chain saw and loading with winch. Average skidding distance is 1 000 m. In addition, Average price of trees is relevant to the composition of

tree species. In the process of optimizing simulation, the composition of tree species is supposed to keep the same in order to simplify the research. But average tree price is different for the stands with different composition of tree species. The average stumpage price simulated is 144.74 (Yuan/m³) with d.b.h of 10–20 cm, 332.15 (Yuan/m³) with d.b.h. of 22–36 cm, 531.69 (Yuan/m³) with d.b.h. of 38–48 cm and 666.49 (Yuan/m³) with over 50 cm in d.b.h. respectively.

The selective cutting cycle (C) and stand structure parameters such as R_{BA} , q and L_{DT} have significant effect on the objective functions such as net profits or harvesting yield of large diameter trees. Simulation results (Table 6) showed that net profits and harvesting yield of large diameter trees changed with the different combinations of C , R_{BA} , q and L_{DT} . When the combination of C , R_{BA} , q and L_{DT} makes objective function gain maximum value, those parameters are called optimum stand structure parameters and optimum selective cutting cycle. Table 6 indicated the optimum stand structure parameters and optimum selective cutting cycle under given R_{BA} . The simulation results of net profits (Table 6) showed that the optimum net profits (accumulative value in 100a) increase as the increment of R_{BA} . When R_{BA} is more than 26 m², the variation of net profits tends to stable status, with average value of 173493 (± 303.56) Yuan/hm² per hundred year. When R_{BA} is less than 20 m², optimum structure parameters are as follows: $L_{DT} = 42$ cm, $q = 1.2$, $C = 30$ a. When R_{BA} is 20–35 m², optimum structure parameters are: $L_{DT} = 46$ cm, $q = 1.2$, $C = 15-30$ a. When R_{BA} is more than 36 m², optimum structure parameters are: $L_{DT} = 46$ cm, $q = 1.1$, $C = 10-15$ a. Except R_{BA} is 40 m², when R_{BA} is 30 m², net profits reaches to optimum, 173914 Yuan/hm² per hundred year, and the optimum stand structure parameters are: $R_{BA} = 30$ m², $L_{DT} = 46$ cm, $q = 1.2$, $C = 15$ a.

Harvesting yield of large diameter trees (accumulative value in 100a) increases as the augment of R_{BA} . When R_{BA} reaches to 26 m², the increment of harvesting yield tends to stable status. When R_{BA} is from 34 m² to 37 m², harvesting yield reaches to the peak point, 398 m³/hm². Optimum stand structure parameters corresponding to the harvesting yield are as follows: $R_{BA} \geq 26$ m², $L_{DT} = 42$ cm, $q = 1.1-1.2$, $C = 5$ a.

According to the above analysis, the optimum stand structure parameters of net profits and harvesting yield of large diameter

trees are different. If stand structure parameters was determined by optimum net profits, optimum stand structure of harvesting yield of large diameter trees cannot be gained, and vice versa. In order to solve the contradiction, the simulation parameters were made by balancing both net profits and harvesting yield of large diameter trees. The simulation parameters were ordered by the largest harvesting yield of large diameter trees. Then, they were secondly ordered by the largest net profits for those stand structures whose harvesting yield of large diameter trees was not less than 5% of the largest harvesting yield. In this way, maximum value of both harvesting yield and net profits with different R_{BA} can be achieved. The analytical results in Table 6 indicate that net profits and harvesting yield of large diameter trees increase as the increment of R_{BA} , but when R_{BA} reaches to 26 m², the increment of net profits tends to stable status, with increasing

rate of 1%–2%. When R_{BA} reaches to 28 m², the increment of harvesting yield also tends to stable status, with fluctuating rate under 2.5%.

The effect of q on optimum stand structure in Table 7 indicate that net profits and harvesting yield of large diameter trees all come to peak points when q is 1.1 and 1.2. Then, the net profits and harvesting yield of large diameter trees begin to decrease gradually.

The effect of largest diameter residual tree (L_{DT}) on optimum stand structure in Table 8 showed that net profits increased as the increment of L_{DT} . When L_{DT} reaches to 46 cm, net profits come to the largest value. And then, L_{DT} continues to increase and net profits begin to decrease. The variation regularity of harvesting yield with the change of diameters is the same as that of net profits, but the peak point is in diameter class of 42 cm.

Table 6. Optimum stand structure by each R_{BA}

Optimum parameters of net profit					Optimum parameters of harvesting yield of large diameter trees					Optimum parameters of balancing net profits & har- vesting yield of large diameter trees				
R_{BA} (m ² /hm ²)	L_{DT} (cm)	q	C (a)	Net profits (Yuan/hm ²)	L_{DT} (cm)	q	C (a)	Harvesting yield (m ³ /hm ²)	q	L_{DT} (cm)	C (a)	Net profits (Yuan/ hm ²)	Harvesting yield (m ³ /hm ²)	
16	42	1.2	30	156630	34	1.2	30	367	1.2	42	25	155906	363	
18	42	1.2	30	161267	38	1.2	30	375	1.2	42	25	160730	372	
20	46	1.2	20	165485	42	1.2	25	381	1.2	46	25	165221	369	
22	46	1.2	20	168667	42	1.2	25	387	1.2	46	25	168353	376	
24	46	1.2	25	171107	42	1.2	5	393	1.2	46	20	170848	381	
26	46	1.2	20	172607	42	1.2	5	395	1.2	46	15	172564	385	
28	46	1.2	15	173060	42	1.2	5	394	1.2	46	10	172907	388	
30	46	1.2	15	173914	42	1.1	5	395	1.2	46	10	173010	388	
32	46	1.2	15	173344	42	1.1	5	397	1.2	46	10	173160	387	
34	46	1.2	15	173267	42	1.1	5	398	1.1	46	15	172935	385	
36	46	1.1	15	173626	42	1.1	5	398	1.1	46	10	173534	389	
38	46	1.1	10	173446	42	1.1	5	397	1.1	46	15	173378	385	
40	46	1.1	10	174044	42	1.1	5	397	1.1	46	15	173722	386	

Notes: R_{BA} : residual basal area; L_{DT} : largest diameter residual tree; q : the ratio of the number of trees in a given diameter class to those in the next larger diameter class; C : selective cutting cycle.

Table 7. Relationship between q and net profits and harvesting yield of large diameter trees

Optimum parameters of net profit					Optimum parameters of harvesting yield of large diameter trees			
q	L_{DT} (cm)	R_{BA} (m ² /hm ²)	C (a)	Net profits (Yuan/ hm ²)	L_{DT} (cm)	R_{BA} (m ² /hm ²)	C (a)	Harvesting yield (m ³ /hm ²)
1	46	40	20	167110	42	40	5	389
1.1	46	40	10	174044	42	37	5	398
1.2	46	30	15	173914	42	27	5	395
1.3	46	40	15	170933	42	36	5	386
1.4	46	40	25	169878	42	40	10	385
1.5	46	40	25	167436	42	40	25	381
1.6	46	38	25	165010	42	40	25	377

Table 8. Relationship between L_{DT} and net profits and harvesting yield of large diameter trees

Optimum parameters of net profit					Optimum parameters of harvesting yield of large diameter trees			
L_{DT} (cm)	q	R_{BA} (m ² /hm ²)	C (a)	Net profits (Yuan/hm ²)	q	R_{BA} (m ² /hm ²)	C (a)	Harvesting yield (m ³ /hm ²)
30	1	30	30	136830	1	30	25	361
34	1	38	30	154896	1	39	25	373
38	1.1	36	30	161431	1.1	32	25	383
42	1.1	35	25	168296	1.1	37	5	398
46	1.1	40	10	174044	1.1	40	5	395
50	1.6	39	25	152582	1.6	31	25	351
54	1.6	34	30	150030	1.6	34	25	347

The effect of selective cutting cycle on optimum stand structure in Table 9 shows that net profits reach to the peak point, respectively 174044 Yuan/hm² per one hundred year and 173914 Yuan/hm² per one hundred year when selective cutting cycle is 10a and 15a. The harvesting yield of large diameter trees de-

creases as the increment of selective cutting cycle, but decreasing rate is slower, less than 8%. The result indicated that selective cutting cycle should be theoretically reduced in order to get higher harvesting yield.

Table 9. Relationship between selective cutting cycle *C* and net profits & harvesting yield of large diameter trees

<i>C</i> (year)	Optimum parameters of net profit				Optimum parameters of harvesting yield of large diameter trees			
	<i>q</i>	<i>L</i> _{DT} (cm)	<i>R</i> _{BA} (m ² /hm ²)	Net profits (Yuan/hm ²)	<i>q</i>	<i>L</i> _{DT} (cm)	<i>R</i> _{BA} (m ² /hm ²)	Harvesting yield (m ³ /hm ²)
10	1.1	46	40	174044	1.1	42	39	395
15	1.2	46	30	173914	1.1	42	40	392
20	1.2	46	29	172984	1.1	42	37	391
25	1.2	46	27	172178	1.1	42	35	389
30	1.1	46	40	171567	1.1	42	35	386

Conclusions and discussion

The variation of stand structure parameters has obvious effect on harvesting yield and net profits of large diameter trees. If optimum stand structure parameters can be used as guidelines in the process of forest cutting and forest cultivation, harvesting yield and economic benefits will be greatly improved.

(1) In theory, if net profits are not considered, the optimum stand structure parameters with high harvesting yield are: $q = 1.1-1.2$, $L_{DT} = 42\text{cm}$, $R_{BA} \geq 26\text{ m}^2$, $C = 5\text{a}$.

(2) The optimum stand structure parameters of net profits are: $q = 1.1-1.2$, $L_{DT} = 46\text{cm}$, $R_{BA} \geq 27\text{ m}^2$, when selective cutting cycle is 10–15 a. In the meanwhile, the optimum stand structure parameters combining net profits and harvesting yield are: $q = 1.1-1.2$, $L_{DT} = 46\text{cm}$, $R_{BA} \geq 26\text{ m}^2$, and selective cutting cycle is 10–20 a.

(3) In the process of forest management, residual basal area (R_{BA}) should be less than 30 m² considering practice. Therefore, according to the difference of stand conditions, R_{BA} for 15 m², 20 m², 25 m² and 30 m² can be selected. And the corresponding optimum stand structure parameters combining net profits and harvesting yield are respectively as follows: $q = 1.2$, $L_{DT} = 42\text{ cm}$, $C = 30\text{ a}$; $q = 1.2$, $L_{DT} = 46\text{cm}$, $C = 25\text{ a}$; $q = 1.2$, $L_{DT} = 46\text{ cm}$, $C = 20\text{ a}$; $q = 1.2$, $L_{DT} = 46\text{ cm}$, $C = 10\text{ a}$.

(4) When initiative conditions of stand structure change, average tree price will vary from the change of composition of tree species. Therefore, the simulation results will be changed partly.

If the tree prices are adjusted by market change, the simulation results will be affected.

References

- Buongiorno, J. and Michie, B.R. 1980. A matrix model of uneven-aged forest management [J]. *For. Sci.*, **26**(4): 609–625.
- Ek, A.R. 1974. Nonlinear models for stand table projection in Northern hardwood stands [J]. *Can. J. Forest Res.*, **4**: 23–27.
- Gove, J.H. and Fairweather, S.E. 1992. Optimizing the management of uneven-aged forest stands: A stochastic approach [J]. *For. Sci.*, **38**: 623–640.
- Hann, D.W. and Bare, B.B. 1979. Uneven-age forest management: State of the art (or science?) [R]. USDA For. Serv. Gen. Tech. Rep. INT-50, 18p.
- Hao Qingyu, Wang Lihai. 2006. Stand Structure Analysis for Managing Natural High-yield Broadleaved Forest in Forest Area of Changbai Mountain [J]. *Forest Engineering*, **22** (1)1–4. (in Chinese)
- Kimmins, J.P. 1990. Modeling the sustainability of forest production and yield for a changing and uncertain future [J]. *For. Chron.*, **66**: 271–280.
- Lin Chingrong, Joseph Buongiorno. 1997. Fixed versus variable-parameter matrix models of forest growth: the case of maple-birch forests [J]. *Ecological Modeling*, **99**: 263–274.
- Mendoza, G.A. and Setyarso, A. 1986. A transition matrix forest growth model for evaluating alternative harvesting schemes in Indonesia [J]. *Forest Ecology and Management*, **15**: 219–228.
- Volin, V.C. and Buongiorno, J. 1996. Effects of alternative management regimes on forest stand structure, species composition, and income: a model for the Italian Dolomites [J]. *For. Ecol. and Manag.*, **87**: 107–125.